Possible use of a narrow-field star tracker on the New Millennium SSI mission

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ABSTRACT

A Separated Spacecraft Interferometer (SSI) Demonstration Mission with three spacecraft has been proposed for flight under the NASA New Millennium Technology Development Program. Both the rotation rate of the interferometer about the normal to the plane containing the three spacecraft and the orientation in the plane must be determined accurately in order to permit the detection of white light fringes from sources that have visual magnitudes as high as possible. It presently is planned to use signals from tracking the science object plus other auxiliary information to determine the interferometer rotation rate $d\theta/dt$ and the angular position θ.

We have investigated a possible supplementary approach that makes use of a combined beacon tracker and narrow-field star tracker on one of the two collector spacecraft. A very small beacon mounted on the other collector spacecraft can be viewed with respect to a reference star nearly 180° away to determine $d\theta/dt$ and θ for the interferometer. Beacon/star tracker observations over roughly an hour appear sufficient to determine the sweep rate for starlight fringes in the interferometer to adequate accuracy and to detect the fringes.

Keywords: separated spacecraft interferometry, space interferometer, narrow-field star tracker, starlight fringe detection, NASA New Millennium Program, space technology development

1. GENERAL APPROACH

For the Separated Spacecraft Interferometry (SSI) demonstration mission, also known as the Deep Space-3 (DS-3) mission of the NASA New Millennium Technology Demonstration Program, an important challenge would be the detection of white light fringes from sources with visual magnitude m_v as high as 13 or 14. We understand that the current approach to determining the interferometer rotation rate and angular position is not expected to be able to reach magnitudes this high.

The option currently being considered makes use of the light from the science object in determining the orientation of the interferometer symmetry axis and the rate of change of the axis orientation. After the starlight is reflected from the siderostats in the two collector spacecraft, the 12 cm diameter beams are sent to a pair of 4:1 condenser telescopes on the combiner spacecraft. Half of the light from each beam is focused onto a CCD array with a roughly 30 cm focal length mirror. The positions of the star images on the CCD array plus several types of auxiliary information are used to determine both the starlight path difference s for the interferometer and its rate of change ds/dt.

We have investigated a possible enhancement to the DS-3 mission in which a combined beacon tracker and star tracker is added to one of the collector spacecraft. In this approach, the tracker is mounted on a two-axis motorized gimbal, and servo controlled to follow the beacon. The image of a reference star nearly 180° from the beacon is measured to determine the angular orientation of the baseline between the two collector spacecraft as a function of time, and thus also the rotation rate of that baseline in the plane of the interferometer. It is assumed that other information on the interferometer arm lengths and their rates of change is available to use in determining the approximate difference in path length for the two starlight beams and its rate of change.

The star tracker is a 6 cm diameter Ritchey-Chretien telescope with a fold in the light path between the secondary and a CCD array detector. The beacon tracker looks in the opposite direction and tracks a beacon on the other collector spacecraft. Its optical system is similar, except that the primary diameter is about 1 cm and either a CCD array or a quadrant detector can be used as the detector. The beacon is the output from a laser diode transmitted from a small aperture, amplitude modulated at a few kHz frequency. The beacon tracker contains a narrow-band interference filter in order to reduce the effect of scattered sunlight, either from the other collector spacecraft or from the beacon tracker sun shield.

The combined tracker is designed to be as stable as possible against both systematic errors due to the detectors and variations in geometry due to temperature drifts. Both telescopes have long effective focal lengths to reduce effects due to changes in the image sizes and positions on the detectors. They are mounted close together to minimize differential thermal offsets of their axes. As an example, possible parameters for the star tracker are given in Table 1. A primary-secondary spacing of 25 cm is chosen, and an effective focal length of 3.0 m. The beam diameter at the secondary is 1.0 cm. The CCD array has 1024×1024 elements, with 15 μm pixel size. With this effective focal length and pixel size, a one pixel image displacement corresponds to an angle of 5×10^{-6} rad (1 arc second).

Table 1. Possible narrow-field star tracker characteristics

Primary focal length	30 cm
Primary diameter	6 cm
Secondary focal length	5.5 cm
Secondary diameter	1.2 cm
Tertiary	tilted flat
Primary - secondary separation	25 cm
Effective focal length	3.0 m
Detector	1024x1024 CCD
Pixel size	15 μm
Field of view	0°.9x0°.9

The assumed geometry for the combined tracker is shown in Figure 1. The secondary and the flat folding mirror for the beacon tracker are not shown because of their small size, but the primary and secondary focal lengths and the element spacing are about the same as for the star tracker. One option is to construct the combined tracker from ultra-low expansion glass, with the mirrors installed by hydroxide-catalyzed bonding. The overall dimensions would be about 7 cm × 10 cm × 30 cm, plus a roughly 20 cm long sunshield for the star tracker and a shorter one for the beacon tracker. The motorized gimbal platform on which the combined tracker is mounted can be controlled tightly to keep the beacon tracker pointed at the beacon because of the high signal-to-noise ratio.

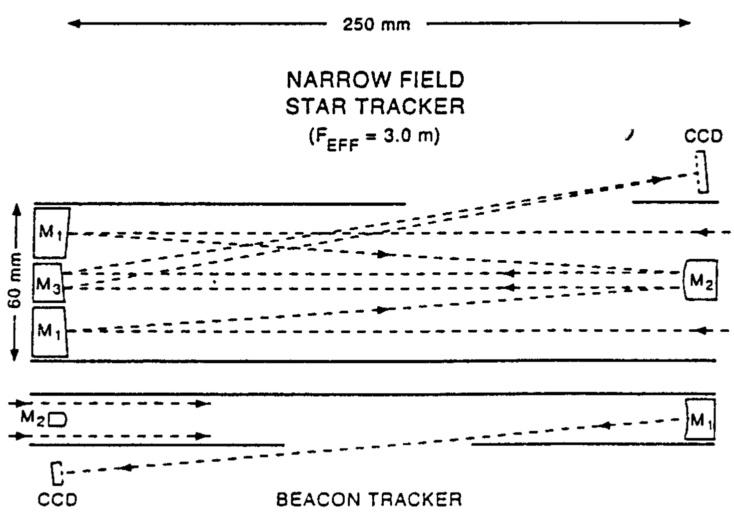

Figure 1. Combined Tracker

With the 1024×1024 element format for the CCD array, the field of view of the star tracker is 0°.9×0°.9. In addition, the orientation of the baselines used to map the UV plane with the interferometer can be altered by ±2° from their ideal values in order to track a brighter guide star. With the resulting 4 sq deg effective field, the chances of a $m_v = 10$ or brighter guide star being available are high. Thus the tracker performance will undoubtedly be limited by systematic errors rather than random noise, and a smaller telescope aperture could be used if necessary. To be specific, we assume after calibration that the systematic e rror of the combined tracker for determining changes in the beacon direction with respect to the star is 1/60 pixel over an observing time of up to roughly 5,000 sec, in a sense that will be specified in the next section. The bias in determining the actual beacon direction with respect to the reference star rather than changes in it is assumed to be 1/30 pixel.

For finding the white light fringe with the DS-3 interferometer, the uncertainties in both the path difference s and its rate of change ds/dt are important. We assume that microwave plus laser measurements of the differences in interferometer arm lengths plus their rates of change permit the interferometer-plane component θ of the collector-collector baseline orientation and changes in it $d\theta/dt$ to be converted into s and ds/dt with little loss in accuracy. A short preliminary observation permits the relative spacecraft motion to be adjusted so that $d\theta/dt$ will be small. Then the initial measurement of the new $d\theta/dt$ is made from $t_0 = 0$ to $t = T$. This is followed by continued measurement of $d\theta/dt$ plus the search for the starlight fringe from $t = T$ to a final time T_f.

2. ERROR MODEL

In order to consider the results that can be achieved, we need to invoke a specific model for the nature of the systematic measurement errors of the beacon/star tracker. The simplest type of systematic error model to use is one in which an effective upper limit L can be placed on the error at any time t in determing the interferometer rotation rate $d\theta/dt$, and a similar limit C can be placed on the angular position θ. We assume that C is a constant, and that $L = D\cdot(T/t)$, where D is a constant. For C we take our assumed bias of (1/30) pixel mentioned earlier, or $C = 2\times10^{-7}$ rad.

The question of what value to assume for D is a more difficult one. We assume that the worst time-dependent errors are first and second degree orthogonal polynomials in the time t', where $0 < t' < t$:

$$F_1 = 2(t'/t) - 1; \qquad F_2 = 6(t'/t)^2 - 6(t'/t) + 1. \tag{1}$$

The coefficients for these functions in the time-variable systematic error u(t') are taken to be α_1 and α_2. The measured angular position $\theta(t)$ is fit up to time t to determine θ and its first two time derivatives as well as possible at that time. A quadratic term in (t'/t) is included to allow for an angular acceleration of the baseline due to the difference in solar radiation pressure on the two collector spacecraft. As a crude but roughly plausible model, we assume each of the terms F_1 and F_2 contributes 25% of the mean square systematic error, $\langle[u(t')]^2\rangle = \sigma^2$. This gives $\alpha_1 = [(\sqrt{3})/2]\sigma$ and $\alpha_2 = [(\sqrt{5})/2]\sigma$. The effect of the rest of the time-variable systematic error is ignored. Thus we approximate (du/dt')(t) by $2\alpha_1 + 6\alpha_2$, with a value for the sum of $8.4\sigma/t$.

Our assumption of (1/60) pixel rms time-variable systematic error in θ mentioned earlier corresponds to $(\sigma) = 0.83\times10^{-7}$ rad. With the above model, this gives an error in $[d\theta/dt]$ at time t of $[(7\times10^{-7})/t]$ rad/s, or $D\cdot T = 7\times10^{-7}$ rad. To simplify the fringe search model, we treat this as an upper limit on the error in $d\theta/dt$. We assume in this article that the baseline length B = 1 km, and thus the maximum error in ds/dt is $B\cdot D\cdot(T/t)$, or $[(7\times10^{-4})/t]$ m/s. Similarly, our assumed value of $C = 2\times10^{-7}$ rad corresponds to a maximum possible error in s of 2×10^{-4} m.

3. FRINGE SEARCH MODEL

The next step is to adopt a model for how the fringe search can be done. Let the extra path difference introduced by the delay lines in order to search for the fringe be w(t) and the maximum fringe rate at which the white light fringe can be detected rel iably be R. Thus it is assumed that the delay line delay tracks the measured path difference s(t), and an additional delay w(t) is introduced to search for the fringe. The suggested search model starts with w(t) = 0 for 0 < t < T. Here T is defined as the time at which the uncertainty in the rate of optical path change ds/dt due to the rotation of the interferometer, as estimated by the beacon/star tracker, becomes equal to R times the effective fringe wavelength λ:

$$B\cdot D = (7\times10^{-4}\ \text{m})/T = \lambda R\ . \tag{2}$$

For $\lambda = 5\times10^{-7}$ m, this gives RT = 1400. As an example, R = 0.5/s is likely to require roughly 50 detected photoelectrons per second for moderate fringe visibilities.[1,2]

At time T, w is offset to -B·C. The derivative of w for t > T is set equal to λR minus the uncertainty in ds/dt:

$$dw/dt = [\lambda R - (B \cdot D \cdot T)/t] \tag{3}$$

Integrating and using eq. 2 gives:

$$w(t) = - B\cdot C + [\lambda R][(t-T) + T \ln(t/T)]. \tag{4}$$

The above fringe search model will clearly lead to fringe detection before a final time T_f such that $w(T_f) = B\cdot C$. However, the model has not been compared with other approaches. We use it only as an example of the kind of search procedure that might be used, and to give a rough estimate of the search time needed for success.

4. RESULTS

Putting in numerical values, as estimated earlier:

$$w(t) = -2\times10^{-4} \text{ m} + [(7\times10^{-4} \text{ m})/T][(t-T) + T \ln(t/T)], \tag{5}$$

$$[w(t)]/[\lambda RT] = -0.3 + [(t-T) + T \ln(t/T)]/T. \tag{6}$$

It can be seen that putting $w(T_f) = B\cdot C$ corresponds to setting the right side of the last equation equal to 0.3, and gives the maximum time T_f necessary to both determine the interferometer rotation rate and find the white light fringe. At time T_f, all cases for which the actual path difference was within a band of width $2\delta s = 2B\cdot C$ about the measured value s(t) for $T < t < T_f$ will have been covered. The resulting equation for T_f is:

$$[(T_f/T) - 1 + \ln(T_f/T)] = 0.6 \ . \tag{7}$$

The solution is $T_f = 1.32$ T.

For our example of R = 0.5/s and roughly 50 detected photoelectrons per second, we understand that the source brightness corresponds to visual magnitude $m_v = 14$ for the DS-3 baseline instrument design and for sources with A5 or earlier spectral type.[3,4] Since RT = 1400 was estimated earlier, finding fringes with such sources would require T ~ 2800s, and a maximum combined rotation rate measurement and search time T_f of roughly 3700 s. It is significant that doubling the path difference uncertainty would only increase T_f to about 4700 s, so minimizing the uncertainty in the interferometer rotation rate uncertainty should be the main objective for the system. The average search time would be somewhat less. For a source magnitude of m_v = 13, a factor 2.5 larger uncertainty in the interferometer rotation rate would be acceptable

Despite the rough nature of the systematic error and fringe search models described above, and the lack of detailed numerical calculations, we believe that the resulting estimates indicate the usefulness of the combined beacon and star tracker approach for permitting DS-3 observations on higher magnitude sources than otherwise would be possible. However, this conclusion clearly is dependent on other sources of error being kept smaller than those due to the beacon/star tracker.

5. ACKNOWLEDGMENTS

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6. REFERENCES

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